Battery Battering: Impact of increased weight of battery and hydrogen zero emission vehicles on road wear.

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Acknowledgements & Funding

JML is partly funded by the University of Edinburgh.

RSH is funded by EPSRC UKCCSRC 2017 EP/P026214/1 and HyStorPor P/S027815/1, and Scottish Gas Networks Academic Alliance H100 project from Ofgem.

GPH is the Bert Whittington Chair of electrical power engineering with the University of Edinburgh, Edinburgh, U.K.

Keywords: hydrogen, battery, BEV, HFCEV, road maintenance, hidden cost.

Abstract

In order to meet global climate targets, it will be essential to decarbonise transport along with emissions sources. For road transport, the two currently available technologies are battery electric vehicles and hydrogen fuel cell electric vehicles. Battery vehicles are more established than hydrogen, although both are capable of delivering the emissions reduction required.

However, battery electric vehicles are usually considerably heavier than the equivalent hydrogen fuel cell electric vehicles, which are in turn slightly heavier than existing internal combustion engine (ICE) vehicles; a heavier vehicle will have a bigger impact on road wear, and associated maintenance and particulate emissions.

Here we examine for the first time one impact and hidden cost, associated with the increased weight of zero emissions vehicles, not commonly addressed in energy research – the additional wear and tear on roads, associated with road maintenance cost and particulate emissions. We examine these in three different future scenarios of all battery vehicles, all hydrogen vehicles, and a combination, in comparison with the current ICE situation.

We find that there is 30-40% additional road wear associated with battery vehicles compared to ICE vehicles; there is a 6% increase from ICE vehicles with hydrogen. This is overwhelmingly caused by the largest vehicles - buses and heavy goods vehicles. The contribution from cars, vans and motorcycles is negligible with any fuel type. Governmental bodies will become liable for increased road maintenance costs and may wish to set weight limits on roads, or require additional axles on heavier vehicles, to decrease road wear.

Graphical Abstract

Introduction

Decarbonisation of energy used in road transport will be essential for the world to meet the necessary reductions in emissions. The two currently commercially available technological solutions for road vehicles are Battery Electric Vehicles (BEV) and Hydrogen Fuel Cell Electric Vehicles (HFCEV) (Robinius et al. 2018). At present, HFCEV vehicles are in their infancy, while BEVs are more established. However, in the UK, Zero Emission Vehicles (ZEV) of any type have not yet made significant inroads into the hydrocarbon fuelled internal combustion engine (ICE) fleet with less than 1% of the vehicle fleet and about 4.3% of new vehicle sales in 2020 (UK Government 2021a, Scottish Government 2020b).

HFCEV are typically slightly (1-2%) heavier than ICE vehicles; BEVs are usually significantly heavier (10-30%) due to the high weight of batteries (Lombardi et al. 2020).

In this paper we apply existing knowledge of the relationship between vehicle weight and road wear to consider the impact of the heavier ZEVs. A significant increase in wear would lead to a combination of increased maintenance costs, increased particulate emisions, and potentially the need to construct new roads to a higher standard.

We select Scotland as an area of analysis. This allows analysis of a fairly homogenous road construction and vehicle standard (Low et al. 2020). This is also connected with the Scottish Government's commitment to unusually demanding targets for early decarbonisation, with a ban on new hydrocarbon car & LGV sales, and an all-sector emissions reduction of 75% from 1990 levels, to be achieved by 2030, followed by net zero emissions by 2045 (Scottish Government 2019), and also with the Scottish Government's recent announcement of substantial investment in the hydrogen economy (Scottish Government 2020a).

This approach can be applied to other locations, subject to local factors such as (i) existing road quality and construction standards, (ii) typical vehicle weight, numbers and construction & use regulations, and (iii) an assessment of the local applicability of the method of road wear assessment used (Rhodes 1983).

Context

There have been several relevant studies investigating the connection between vehicle weight and road wear, starting with seminal work by the American Association of Highway and Transportation Officials (AASHO) in the 1950s (AASHO 1962). This was further developed in the UK by Rhodes (Rhodes 1983) and the Transport Research laboratory (Addis and Whitmarsh 1981), and re-examined by Martin in 2002 with a focus on Australian roads of similar construction (Martin 2002), confirming the relationship first developed.

Nilsson, Svensson and Haraldson (Nilsson et al. 2020) assess the economic impact and life between major restoration of road surfaces subject to different types of loading. However, their results also find additional surface wear due to smaller vehicles. They attribute this to the use of studded snow tyres in their study area, Sweden, which are not used in Scotland.

Gustafsson (Gustafsson 2018), Denby, Kupiainen and Gustafson (Denby et al. 2018) and Stafoggia and Faustini (Stafoggia and Faustini 2018) review the impact and measurement of road wear emissions on public health, within *Non-Exhaust Emissions: an Urban Air Quality Problem for Public Health; Impact and Mitigation Measures* (Amato 2018).

Lombardi, Tribioli, Guandalini and Iora (Lombardi et al. 2020) examine the impact of different drivetrain types, including HFCEV and BEV on the weights of a range of vehicles, as part of their analysis into efficiency.

Here, we draw together these strands to examine the impact of increased future vehicle weight from fuel cells or batteries, due to heavier zero-emission drivetrains, and consider their impact on road wear and hence road maintenance and particulate emissions.

Method

Rhodes(Rhodes 1983) (and many others) describes the 4th power relationship between road wear and axle load, developed from the experimental work on the subject by the AASHO in the 1950s (AASHO 1962). Rhodes introduces the concept of using a Standard Axle as a way of comparing the impact of various vehicle types. The Standard Axle is taken as a single axle imposing a total load of 80kN (equivalent to 8 tonnes); the wear relative to such an axle can be readily calculated using the 4th power to give a number of effective standard axles per actual axle. We express this mathematically in Equation *1* below.

Effective Standard Axles = (Axle load in kN / 80)^4 *Equation 1*

This approach allows an assessment of cumulative impact of vehicles of different classes, and is used in other studies into road wear (Nilsson et al. 2020). As road wear is very tightly controlled by axle load, it becomes apparent that larger vehicles such as HGVs and buses will have a much greater impact than cars, relative to the vehicle weight.

Other researchers have developed different relationships - for example the UK Transport and Roads Research Laboratory produced a range of exponential powers between 2.4 to 6.6 depending on a number of factors including existing road condition and construction standard (Addis and Whitmarsh 1981). Johnsson derives a range of powers for Swedish roads between 1.2 and 8.5 (Johnsson 2004). However, for the purpose of this preliminary assessment of the road wear impact by future vehicles, we consider the single 4th power of axle weight to be adequate; this is currently used in UK and many other countries' highways design and maintenance (UK Government 2021b).

Based on this established relationship, we introduce the terms Road Wear Potential (RWP) of an individual vehicle, and the Road Wear Impact Factor (RWIF), reflecting the total annual wear caused, which could apply to each vehicle class, sub-class, or national fleet.

The RWP reflects the potential of a vehicle to wear out the road, without considering the extent to which it is used. It depends on the weight of the vehicle and the number of axles it uses, and uses the above 4th power relationship to determine the number of effective standard axles per vehicle. We assume for these purposes that each axle in a vehicle carries an equal load. In practice this will not be the case; we examine effect of this in the Sensitivities section.

RWP = (Nr. of axles) x (Vehicle Weight/(Nr. of axles x 80))^4 *Equation 2*

The annual RWIF for each class (or sub-class) is based on the Road Wear Potential of a typical vehicle of a given class, multiplied by the average distance such a vehicle drives and by the number of vehicles in each class. This gives an overall value for comparison of the road wear associated with an entire vehicle class over the course of a year.

Class RWIF = RWP(typical in class) x (nr. vehicles in class) x (average annual distance driven) Equation 3

The Class Road Wear Impact Factors are then summed to create an overall RWIF for each scenario.

The inputs and data sources are as follows:

- The number of vehicles in each standard vehicle class (buses & coaches, cars, motorcycles, HGV and LGV) (Scottish Government 2020b)
- The typical weight, or range of weights, or fuel based sub-classes, of ICE vehicles in each class (Scottish Government 2020b).
- The likely change in weight due to a similar vehicle having HFCEV or BEV type fuelling and drive systems (see below for derivation).
- The average annual distance travelled per vehicle by class, in km (UK Department of Transport 2019).
- We assume that the wear and tear is directly related to the use made of the roads, i.e. the number, class and weight of vehicles using the roads, and not significantly connected to seasonal, weather and simple aging related impacts alone (Nilsson et al. 2020).

- We use the standard UK government vehicle classes of cars, motorcycles, Light Goods Vehicles (LGV), Heavy Goods Vehicles (HGV)[1], and Buses & Coaches. HGVs are further divided into ten weight-based sub-classes, while cars and LGVs are divided into fuel based, that is petrol (gasoline) and diesel; the number of BEVs is still small enough to be insignificant) sub-classes.

To estimate the applicable vehicle weight, or reference weight, for ZEVs, we make an initial assessment of the increase in vehicle weight due to the two new fuel types, and derive simple formulas that fit data previously identified by Lombardi et al (Lombardi et al. 2020) and vehicle manufacturers (Mercedes Benz UK 2019).

We calculate the RWP and RWIF for all classes and sub-classes, and hence the nationwide RWIF, for four scenarios:

1. Current situation, vehicle fleet overwhelmingly dominated by ICE vehicles.
2. All BEV – all vehicles replaced in the same numbers and load carrying capacity with BEVs.
3. All HFCEV – all vehicles replaced in the same numbers and load carrying capacity with HFCEVs.
4. Like for Like – all current diesel vehicles replaced by HFCEVs, and all current petrol vehicles replaced by BEVs.

Results

Initial assessment of vehicle weight and other inputs

Based on Lombardi et al (Lombardi et al. 2020) for larger vehicles (3500kg and over), and manufacturers' published data for cars (Mercedes Benz UK 2019), we identify the following equivalent vehicle weights for vehicles of the same carrying capacity:

ICE weight (kg)	BEV weight (kg)	HFCEV weight (kg)
1950	2455	1970
3500	4224	3566
5200	6028	5255
18000	19816	18236
44000	47686*	44760*

Table 1 Gross vehicle weights for equal payload, three fuel types.
*Note that the weight marked * exceed the maximum allowable vehicle weight of 44 tonnes.*

To get a suitable equivalence from manufacturers' data, it is necessary to identify almost identical vehicles made with different fuel types. The only car commercially available both as an HFCEV and as an ICE vehicle is the Mercedes-Benz GLC (now ceased production), which is a medium-large SUV. The HFCEV version has a larger battery than is usual for an HFCEV (13.5kWh instead of around 1.6kWh (Hyundai UK 2020)), and can be used as a plug in hybrid. It is also available as a BEV (called the EQ-C, with some styling differences)(Mercedes Benz, 2022). Other vehicles exist as both BEV and ICE, but not HFCEV. For the purposes of consistency in this table, we use the Mercedes-Benz GLC / EQ-C for both ZEV types. We adjust the weight of the GLC Fuel Cell down by 95kg to reflect the typical extra weight of the larger Li-Ion battery(Jung et al. 2018), to create a more relevant entry for this table.

[1] The Scottish and UK Governments use the terms "Goods" and "Light Goods" for goods vehicles above and below 3,500 kg maximum gross weight respectively. Here, to reduce ambiguity, we use the older common terms Heavy Goods Vehicle (HGV) and Light Goods Vehicle (LGV).

From this table, we derive a simple relationship between the weight of a BEV and an ICE vehicle of the same carrying capacity based on the trendline function in Microsoft Excel, as follows:

$$\text{BEV Weight} = (1.0744 \times \text{ICE Weight}) + 430$$ *Equation 4*

And between an HFCEV and an ICE vehicle:

$$\text{FCEV Weight} = (1.014 \times \text{ICE Weight})$$ *Equation 5*

Both of these formulas match the table 1 data well, with a very close R^2 value of at least 0.9999.

The maximum permitted weight of an HGV is 44,000 kg; clearly the weight of the two ZEV equivalents exceed this value. We address this by assuming that vehicles in this class remain at the limit of 44,000 kg, but they make more journeys and so cover a greater distance each, so that the same total payload is carried over a year. This approach is extended for similar circumstances where the new weight of an HGV sub-class passes the permitted weight, taking account of 1000kg permitted extra weight for 2 axle and 3 axle rigid chassis zero emission HGVs (UK Government 2017).

Given that the lowest data point in the original table still represents a large car, it will be necessary to extrapolate the formula slightly to get a vehicle weight more representative of a smaller one; it may be unrepresentative of motorcycles. However, as it turns out, the RWIF of cars and motorcycles is so low that this immaterial (see below).

For each class or sub-class, we have to estimate a reference vehicle weight. The key factor affecting this for large vehicles is the proportion of time the vehicles run empty or lightly loaded. This will obviously happen some of the time, with a significant change in weight. Vehicle operators will clearly try to maximise the load in their vehicles, so the actual average weight can be expected to be higher than, for example, a mid-point between empty and full. We expect that buses will run for a higher proportion of the time empty or lightly loaded, as they will be sized for peak demand. However, due to the 4^{th} power relationship described above, the heavier loading will have a proportionately greater impact on road wear.

As a working assumption, we take the reference vehicle weight as the midpoint of the applicable weight range. We examine the implications of inaccuracies in the Sensitivities section below.

The annual distance travelled by each vehicle is taken as the average for the class or sub-class from UK government statistics. There are cases where this data is only available for a group of sub-classes (e.g., all 2- or 3- axle rigid chassis HGVs) – in this case we take the average for all relevant sub-classes. This is also examined in Sensitivities, below.

For some sub-classes of HGV, the allowable weight was exceeded when the vehicle weight was increased, as seen in Table 1. In these circumstances, we assume that the maximum weight will not be exceeded, but that the affected vehicles will cover longer distances instead. There are other ways that this could be treated, which we explore further in Sensitivities.

Road Wear Potential per vehicle

We examined the wear potential associated with individual vehicles. Figure 1 below shows the relationship between vehicle weight and Road Wear Impact Factor, taken as the number of standard axles per vehicle. This shows the RWP of a vehicle in each sub-class based on its weight and number of axles, for the three fuel types under consideration.

Figure 1 Road Wear Potential (RWP) per vehicle, sorted by vehicle sub-class, comparing ICE, BEV and HFCEV. RWP is the number of standard axles per axle, multiplied by the number of axles on the vehicle. Vehicles under 3.5t have negligible RWP.

We can see from Figure 1 that the wear potential of a larger vehicle is overwhelmingly greater than that of a smaller one, due to the 4^{th} power law exponentially increasing the effect of greater axle load. We also see a significant increase in wear potential for a relatively small increase in vehicle weight in large vehicles, for the same reason. The mitigating effect of additional axles is also clear – the reduced number of effective standard axles per actual axle more than offsets the increased number of axles, hence the total RWP decreases for vehicles where the axle count increases.   This happens at the 16-20t category, where the axle count increases to 3, at 28-30t where it increases to 4, at 38-40t which requires 5 axles, and 40-44t requiring 6 axles.

Road Wear Impact Factor

Next, we develop this into the assessment of the Road Wear Impact Factor by Class and overall, for the four scenarios under consideration. Multiplying each vehicle's Road Wear Potential by the number of vehicles in the class and the average distance driven each year(UK Department of Transport 2019) produces the total Road Wear Impact Factor for each class. This produces overall sub-class and class Road Wear Impact Factors as shown in Figure 2 below.

Figure 2   Class / Sub-class Road Wear Impact Factor, comparing the present and future scenarios. Road Wear Impact Factor is the Road Wear Potential multiplied by the number of vehicles in each class or sub-class and by the average annual distance travelled. Vehicle classes with a typical vehicle weight below 12t have negligible RWIF on a national scale.

Clearly the overall RWIF is overwhelmingly due to the largest vehicles in use, even though they don't have the highest RWP. This reflects the greater use made of the largest vehicles – there are more 40-44t HGVs than any other category of HGV other than the smallest 3.5-7.5t vehicles, which has about 20% more; also a typical 44t vehicle covers almost twice the annual distance of a 7.5t one. Due to the much smaller RWP, vehicles below 12t, or even 24t, have a negligible impact on national RWIF with any fuel type.

The impact of ZEV technology in larger vehicles can be clearly seen, with BEV having a substantially greater impact than FCEV. This is especially marked in buses, which are permitted to operate with two axles at higher weights than HGVs - 19,500kg for buses, compared to 17,000 kg for ZEV HGVs.

A table with a detailed breakdown of the calculations and results is presented in the Appendix.

Sensitivities

We considered the sensitivity of the results to different ways of estimating the input simplifications:

- Reference weight estimate
- Increasing axle numbers instead of increasing distance covered, when allowable vehicle weight was exceeded;
- Varied load distribution, other than equal on each axle;
- Using HGV subcategories based on axle number rather than tax bracket.

We initially assumed a reference weight at the midpoint between the top and bottom of each tax class. However, the reference weight, or typical effective weight, could be significantly different for HGVs, due to the potential for different loading patterns. We varied the originally estimated reference weight by factors ranging from 0.5 to 1.07. Beyond 1.07, the ICE reference weight began to exceed the allowable weight in each category, particularly the heaviest, therefore a higher factor than this was clearly unrealistic.

We then considered two approaches to dealing with excess weight in future vehicles: either (1) increase the distance travelled, keeping the reference weight at the sub-class maximum, or (2) increase the number of axles required for the sub-class. We found patterns for these two approaches as shown in figures 3 & 4:

Figure 3   Change in RWIF as a consequence of change in modelled ICE reference weight. Where allowable vehicle weight is exceeded, modelled number of axles per vehicle is increased. Step changes are where the axle count for a class or sub-class changes.

Figure 4   Change in RWIF as a consequence of change in modelled ICE reference weight. Where allowable vehicle weight is exceeded, modelled distance travelled per vehicle is increased.

Both approaches show very similar results. The final output, the change in RWIF with different fuels, is assessed as the ratio between the old and the new rather than a meaningful absolute value, so a change to both produces a similar result for most of the range. The change in RWIF decreases at higher scaling factors because the beneficial effect of adding axles or distance travelled becomes significant. On this basis, we describe the change in overall RWIF due to a fully BEV fleet as 30-40%, and for a fully FCEV and Like for Like fleet as 6%.

To assess the effect of unequal load distribution, we considered the effect of one axle carrying a percentage more than all the other axles, which were set as equal. An unevenly distributed load would result in a higher RWP than an evenly distributed one. However, when the same proportion of uneven-ness is applied to current and future cases, the relative increase in RWIF is unchanged. Ensuring that loads are more evenly distributed in ZEVs than at present would be a way of mitigating the increased RWP, but that analysis is beyond the scope of this paper.

Data is available for HGV numbers and usage based on weight related tax bracket or on number of axles, which is also related to maximum weight. Using tax brackets gives a finer division of data; using the axle number gives a better match to the effects between sub-classes and permitted vehicle weights. Our main approach has been to use the former. Here, we re-run the analysis on the basis of axle numbers, for comparison.

However, again because the treatment is the same for ICE and ZEV, the effect on the overall result is minimal. Results are presented in Table 2:

	BEV	**FCEV**	**Like for Like**
% increase in overall RWIF (tax bracket based sub-classes)	29.7%	5.7%	5.9%
% increase in overall RWIF (axle number based sub-classes)	30.2%	5.7%	5.9%

Table 2 Comparison of RWIF for different types of HGV sub-class categorisation.

We consider this effect to be insignificant.

Conclusion and discussion

A complete conversion of the existing vehicle fleet to BEV would be likely to increase annual road wear in Scotland by around 30-40%. Conversely, the same conversion to HFCEV would increase road wear by around 6% (Figure 5).

The combined, or "Like for Like" future fleet, where existing diesel vehicles are replaced by HFCEV and existing petrol vehicles are replaced by BEV, would also lead to increased road wear of around 6%.

We can see**Error! Reference source not found.** that in each scenario, the Road Wear Impact Factor is dominated by the relatively small number of HGVs, 37,000 vehicles out of a total vehicle fleet of approximately 3 million, which contribute around 87% of the Road Wear Impact Factor. The 14,000 buses and coaches are also significant, contributing around 12%. The Road Wear Impact Factors due to cars, light goods vehicles and motorcycles are insignificant, contributing in total less than 1% of the Road Wear Impact Factor in all scenarios. This will not be news to highways engineers, but needs to be understood in the energy sector. HGVs and Buses & Coaches would be HFCEVs in both the all-HFCEV and the Like for Like scenarios; as those are the vehicles overwhelmingly responsible for road wear, this leads to the Road Wear Impact Factors being effectively identical for both of these scenarios.

Figure 5 Overall Road Wear Impact Factors, grouped by class. Subcategory values have been combined to produce the overall class values.

This effect could possibly be mitigated in the future by the introduction of lighter-weight battery technology. This is, however, speculative – while such batteries are being researched, they are not yet commercially available (Ye and Li 2021). It might also be possible to re-engineer the basic vehicle to be lighter by using lighter materials or construction methods, although these would be equally applicable to other fuel types. A further mitigating effect, requiring no new technology, would be to increase the required number of axles on large vehicles – due to the 4th power effect, the reduction in wear per axle would outweigh the extra wear due to the additional axles. This would, however, increase the vehicle manufacturing costs and carbon-free fuel consumption (Johnsson 2004).

The all-BEV scenario represents an increase in road wear of about 30% from the present situation; all HFCEV and Like For Like both represent an increase of about 6% - that they are almost identical reflects the dominance of diesel in large vehicles at present.

It would also be important to design vehicles such that the additional weight of batteries is evenly distributed across all axles – this would prevent an imbalanced load creating significant extra wear. This could, however, force a change in operating practice for articulated HGVs, as some of the batteries would have to be installed in the trailer unit.

In Scotland, responsibility for road maintenance is shared between the Scottish Government for trunk (primary) roads, and local authorities for the much greater network of all other roads from large A-class roads through to urban access; these bodies would bear the costs related to this additional road wear. It has been reported in Scotland that current levels of road maintenance are inadequate at present to sustain existing road quality (Williams 2019). In that case, the greater demands made of the roads in the future that we outline here can be expected to lead to an even faster deterioration (Addis and Whitmarsh 1981). However, we do not assess that impact in this paper.

These additional costs, and the consequence of the additional emissions, should be included when planning the support of different fuel types on a national fleet. The fuel choice of cars, light goods vehicles and motorcycles will make little difference to road wear. However, with more HFCEV buses & coaches and heavy goods vehicles, the overall road maintenance cost will be substantially lower than with those vehicles as BEVs; it will require only a relatively small increase over the current ICE vehicle situation.

Figure 6 Summary conclusion

Author Contributions

JML: Conceptualisation, Method, Investigation, Analysis, Paper structure, Writing – preparation, review and edit.
RSH: Paper structure and content review, Validation, Writing – review, Supervision.
GPH: Paper content review, Validation, Writing – review, Supervision.

Data Availability

The datasets generated during and/or analysed during the current study are available in the GitHub repository, https://github.com/J-M-Low/Battery-Battering.git

Conflicts of Interest

The authors have no relevant financial or non-financial interests to disclose.

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Appendix

Calculation tables.

						Internal Combustion Engine vehicles						
I **Veh. class**	II **Subclass**	III **Number registered in Scotland**	IV **Chassis type (ICE)**	V **Weight range**	VI	VII **Reference weight (ICE)**	VIII **Nr. of axles per vehicle**	IX **Ref. weight / axle**	X **Average annual km, per vehicle**	XI **Standard 80kN axles per axle (ICE)**	XII **RWP**	XIII **RWIF**
Data source or method:	(Scottish Government 2020b)	(Scottish Government 2020b)	(UK Government 2010)	(Scottish Government 2020b)		Calculated (VI - V)/2	(UK Government 2010)	Calc-ulated VII/VIII	(UK Department of Transport 2019)	Calculated (VII/80)^4	Calculated XI x VIII	Calculated XII x X x III
		nr	%	from kg	to kg	kg	nr.	kN	km	nr.	Std. axles / vehicle	million std. axle – km / year
Buses & Coaches		14,154	Two axle rigid	14,000	24,800	17000	2	83	45,471	1.18030	2.36	1,519
Cars	Petrol	1,544,505		1,000	2,600	1,800	2	9	14,571	0.00015	0.000297	7
Cars	Diesel	973,215		1,000	2,600	1,800	2	9	14,571	0.00015	0.000297	4
Motor-cycles		71,666				200	2	1	4,490	negligible	negligible	<0.1
HGV	3.5t - 7.5t	7,986	Two axle rigid	3,500	7,500	5,500	2	27	72,127	0.01293	0.0259	15
HGV	7.5t - 12t	1,275	Two axle rigid	7,500	12,000	9,750	2	48	72,127	0.12771	0.255	23
HGV	12t - 16t	1,238	Two axle rigid	12,000	16,000	14,000	2	69	72,127	0.54289	1.09	97
HGV	16t - 20t	4,656	Three axle rigid	16,000	20,000	18,000	3	59	17,259	0.29304	0.879	71
HGV	20t - 24t	678	Three axle rigid	20,000	24,000	22,000	3	72	17,259	0.65392	1.96	23
HGV	24t - 28t*	5,367	Three axle rigid	24,000	27,000	25,500	3	83	17,259	1.18030	3.54	328
HGV	28t - 32t	4,446	Four axle rigid	28,000	32,000	30,000	4	74	45,693	0.71542	2.86	581
HGV	32t - 38t	637	Four axle articulated	32,000	38,000	35,000	4	86	173,886	1.32540	5.30	587
HGV	38t - 40t	3,958	Five axle articulated	38,000	40,000	39,000	5	77	125,999	0.83694	4.18	2,087
HGV	40t - 44t	6,596	Six axle articulated	40,000	44,000	42,000	6	69	125,999	0.54289	3.26	2,707
LGV	Petrol	9,842		2,500	3,500	3000	2	15	26,262	0.00114	0.00229	592
LGV	Diesel	296,495		2,500	3,500	3000	2	15	26,262	0.00114	0.00229	18
						Total Standard axle -km per year, as Road Wear Impact Factor						**8,068**
All HGVs		36,837										6,520
All Cars		2,524,000										11
All LGVs		308,000										18

*Table A1 Calculation of the Road Wear Impact Factor for the current scenario of an Internal Combustion Engine based national vehicle fleet. Where 'Calculated' is shown at Data Source or Method, Roman numerals in the formula refer to the preceding columns as numbered in the top row. * Max weight set at 27,000 kg, the most allowable for a 3 axle vehicle with ZEV powertrain.*

Battery Electric and Fuel Cell Electric Vehicles		Battery drivetrain weight formula							Fuel cell drive train weight formula						
		BEV weight = 1.0744 x ICE weight + 430.17							HFCEV weight = 1.014 x ICE weight						
I **Vehicle class**	II **Sub-class**	XIII **Reference weight**	XIV **Nr. of axles per vehicle**	XV **Ref. weight / axle**	XVI **Average annual km, per vehicle**	XVII **Standard 80kN axles per axle**	XVIII **RWP**	XIX **RWIF**	XX **Reference weight**	XXI **Nr. of axles per vehicle**	XXII **Ref. weight / axle**	XXIII **Average annual km, per vehicle**	XXIV **Standard 80kN axles per axle**	XXV **RWP**	XXIV **RWIF**
Data source / method:	(Scottish Government 2020b)	From formula above	(UK Government 2010)	Calc: XIII/XIV	(UK Department of Transport 2019)	Calc. (XV/80)^4	Calc. XVII x XIV	Calc. XVIII x XVI x III	From formula above	(UK Government 2010)	Calc: XX/XIX	(UK Department of Transport 2019)	Calc: (XXII/80)^4	Calc. XXIV x XXI	Calc: XXV x XXIII x III
		kg	nr.	kN	km	nr.	Std. axles / vehicle	million std. axle – km / year	kg	nr.	kN	km	nr.	Std. axles / vehicle	million std. axle – km / year
Buses & Coaches		18695	2	92	45,471	1.726	3.45	2,222	17238	2	85	45,471	1.248	2.50	1,606
Cars	Petrol	2364	2	12	14,571	0.0004	0.0008	20	1825	2	9	14,571	0.00016	0.0003	7
Cars	Diesel	2364	2	12	14,571	0.0004	0.0008	13	1825	2	9	14,571	0.00016	0.0003	4
Motor-cycles		645	2	3	4,490	neg.	neg.	<0.1	203	2	1	4,490	neg.	neg.	<0.1
HGV	3.5t - 7.5t	6339	2	31	72,127	0.023	0.0456	26	5577	2	27	72,127	0.014	0.0273	16
HGV	7.5t - 12t	10906	2	53	72,127	0.200	0.400	37	9887	2	48	72,127	0.135	0.270	25
HGV	12t - 16t	15472	2	76	72,127	0.810	1.62	145	14196	2	70	72,127	0.574	1.15	102
HGV	16t - 20t	19769	3	65	17,259	0.426	1.279	103	18252	3	60	17,259	0.310	0.929	75
HGV	20t - 24t	24067	3	79	17,259	0.937	2.81	33	22308	3	73	17,259	0.691	2.07	24
HGV	24t - 28t*	27000	3	88	17,788	1.48	4.45	425	25857	3	85	17,259	1.24	3.74	347
HGV	28t - 32t	32000	4	78	46,638	0.926	3.70	768	30420	4	75	45,693	0.756	3.03	615
HGV	32t - 38t	38000	4	93	174,042	1.84	7.37	817	35490	4	87	173,886	1.40	5.60	621
HGV	38t - 40t	40000	5	78	133,344	0.926	4.63	2,444	39546	5	78	125,999	0.885	4.42	2,206
HGV	40t - 44t	44000	6	72	130,452	0.654	3.92	3,376	42588	6	70	125,999	0.57393	3.44	2,862
LGV	Petrol	3500	2	17	27,413	0.002	0.004	1.1	3042	2	15	26,262	0.00121	0.0024	0.6
LGV	Diesel	3500	2	17	27,413	0.002	0.004	34	3042	2	15	26,262	0.00121	0.0024	19
		Total Standard axle -km per year, as Road Wear Impact Factor						**10,463**							**8,530**
All HGVs								8,173							6,893
All Cars								32							12
All LGVs								36							19

Table A2 Calculation of the Road Wear Impact Factor for the all BEV and all HFCEV scenarios. Where 'Calculated' (or 'calc') is shown at Data Source or Method, the formula is given, with Roman numerals in the formula refer to the preceding columns as numbered in the top row.